SQUID Array Microscope—An Ultrasensitive Tool for Nondestructive Evaluation

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Introduction

Nondestructive evaluation, or NDE, is a field devoted to finding out if objects are developing fractures, flaws, or other mechanical problems without actually having to rip the object apart to find out. This can be very valuable if your object is something like an aircraft wheel, subject to enormous stress every day and prone to getting cracks in places where you can't see them without removing the wheel and disassembling it. The NDE of an aging nuclear weapon can save large amounts of time and expense by showing what is happening to it on the inside without actually having to open it up. Conventional NDE techniques include ultrasound, x-rays, and conventional eddy-current testing. Eddy-current inspection works by injecting or inducing currents into a conducting sample and then looking at how these currents flow. If the sample has no flaws, the current will flow unimpeded. If the sample contains a flaw, such as an inclusion or rust spot, the current will flow differently through that material. If the flaw is a crack, the current will flow around it (see Figure 1).

The trick is in the measuring of how the currents are flowing. Conventional eddy-current techniques use a receiver coil and measure the impedance changes as it scans across the sample. In the Biophysics group at Los Alamos, we have developed a system that replaces the receiver coil with a linear array of superconducting quantum interference devices (SQUIDs). The array of SQUIDs measures the magnetic fields produced by the eddy currents in the sample directly. The result is an NDE system that has unsurpassed sensitivity to features that are very small or buried deeply.

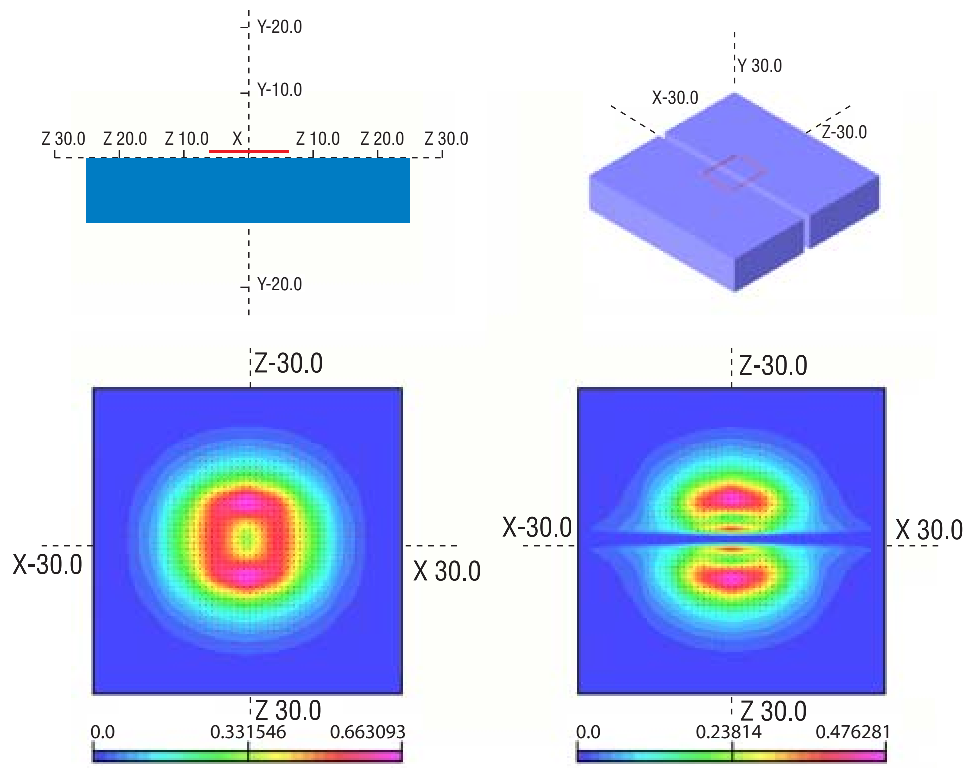

Figure 1. Left: As illustrated in a simple eddy current simulation, in a sample with no flaws the current flows unimpeded. Right: The simulation shows that in a sample with a flaw, the current has to deviate. This produces the magnetic-field anomaly measured by the SQUID.

What Is a SQUID?

The top panel of Figure 2 shows an example of the species of SQUID we are discussing. The SQUID is a loop of superconducting material (made of either low- [liquid helium: 4 K] or high-temperature [liquid nitrogen: 77 K] superconducting material) that is interrupted by two weakly superconducting regions known as Josephson Junctions. During operation of a SQUID, a bias current is applied to the device. Up to some critical biasing current, there is no voltage across the SQUID. It acts as a superconductor and current flows without resistance. However, above the critical bias-current level, the junction becomes resistive and a voltage does appear across the device. This is roughly analogous to water flowing in a hose with a kink in it. Once the device shows this voltage, it behaves very interestingly—the quantum-mechanical wave functions which describe the electrons in the SQUID on either side of the Josephson Junctions interfere with each other. As a result, the voltage across the SQUID, for a fixed bias current, oscillates. The oscillation is a function of the amount of flux that is threading through the SQUID loop, as shown in Figure 3. The period of this oscillation is called the flux quantum, (Φ_0). One Φ_0 is equivalent to the amount of magnetic flux from the Earth's magnetic field passing through an area the size of one human red blood cell. A SQUID is sensitive to changes in magnetic flux as small as one millionth of one Φ_0!

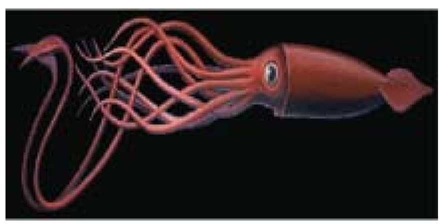

Figure 2. Bottom: A squid, not the type we are talking about. Top: a superconducting quantum interference device, SQUID.

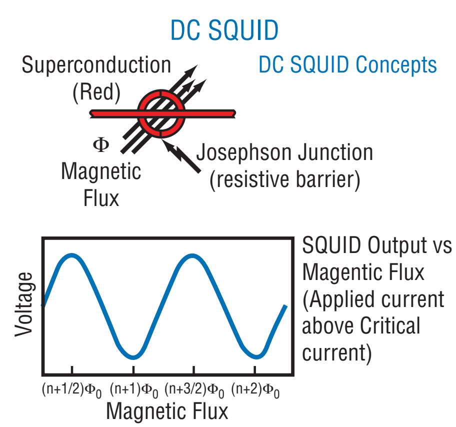

Figure 3. A bias current is applied so that the SQUID has a voltage across it. This voltage will oscillate depending on the amount of magnetic field passing through the SQUID loop.

Why Use a SQUID?

SQUIDs can be appropriate for some NDE problems because they are the most sensitive detector of magnetic flux known. In particular, SQUIDs can be well suited to the problem of buried features. A technique such as conventional eddy-current NDE has to go to lower eddy-current frequencies (ω) to get the required skin depth (δ). This dependence is shown in Equation 1,

$$\delta = \sqrt{\frac{2\rho}{\omega\mu_0}}\,, \qquad (1)$$

where ρ is the resisitivity of the material. However, the voltage measured is proportional to the frequency, $V \propto \omega$. To see a flaw 1 cm deep in an aluminum plate, conventional eddy-current NDE requires ω less than 100 Hz. This is a difficult regime for conventional eddy-current testing, whereas SQUIDs are uniformly sensitive at frequencies from near DC to megahertz.

Other NDE techniques also have limitations. Ultrasound has difficulties with signal reflection at the boundaries of material layers that are sonic absorbers (most plastics and electrical insulators), which reduces the technique's sensitivity to features below such layers. Radiographic techniques can be expensive, nonportable, and insensitive to small one-dimensional features.

SQUIDs can be appropriate for some NDE problems because they are the most sensitive detector of magnetic flux known. In particular, SQUIDs can be well suited to the problem of buried features. SQUID sensitivity does not depend on frequency, enabling these sensors to be used for detecting features and defects over a broad range of material depths. Furthermore, the induction signal at a given frequency depends only on ρ, not on gaps or intervening layers. Also, a SQUID system can be portable and relatively inexpensive.

SAMi

The SQUID array microscope (SAMi) was developed for the stockpile-stewardship program at Los Alamos National Laboratory. SAMi is capable of finding features that are small and buried at depths of 1 cm or much more. SAMi is the first instrument of its kind to use a linear array of 11 high-temperature SQUIDs spaced 0.75 mm apart. A picture of the SQUID array is shown in Figure 4. All the SQUIDs were manufactured on a single chip. This means that their geometry is well understood and their performance characteristics are very uniform. Using an array such as this affords two distinct advantages: decreased scanning time and increased resolution.

Another advantage to the SAMi system is that it can induce an eddy current at a single frequency like a conventional NDE system or use a unique white-noise induction scheme (patent pending) to induce at multiple frequencies at the same time. As we showed in Equation 1, the skin depth to which these eddy currents penetrate the sample depends on the frequency. Using white-noise induction, the SQUID's response at multiple skin depths (frequencies) can be simultaneously acquired and analyzed. The operator then uses the response to extract information about the feature depth and character.

The fiberglass SAMi dewar was custom built with a ~4 mm hot-cold distance. The SQUIDs as well as the induction coil are in the liquid nitrogen bath. Samples are scanned beneath the dewar by a dual-axis translation stage. A schematic diagram of the SAMi dewar and a picture of the system operating in our laboratory are shown in Figures 5 and 6.

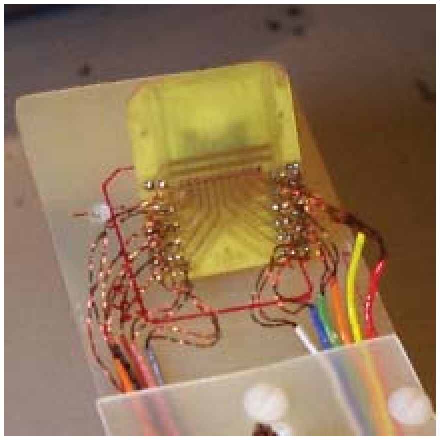

Figure 4. The SAMi uses a linear array of 11 SQUIDs.

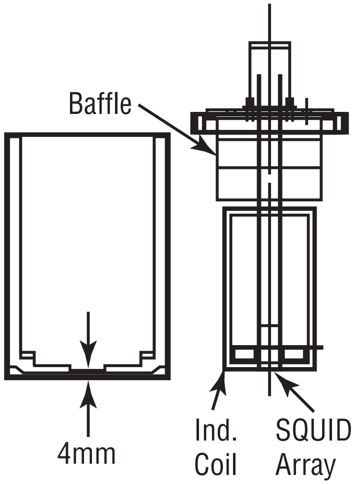

Figure 5. A schematic drawing of the SAMi dewar and insert.

Figure 6. The SAMi system. A sample is positioned below the white dewar. The motion-control stage scans the samples below the SQUIDs.

SAMi Results

Laser Welds

A quality-control issue important to stockpile stewardship and industrial applications is the inspection of the quality of laser welds. We inspected welds in samples of incoloy 825. The samples consisted of two 20 mm × 76 mm plates of ~3 mm thickness. The plates were laser welded in three places along their length. Energy and focus of the welding laser were varied for each of the welds. The results are shown in Figure 7. The different curves are SAMi scans for welds of different laser energies. Notice that for the weld at a laser energy of 2.5 J (solid blue line, upper panel) there is a fairly deep "dip" in the data. If there were no weld, there would be no change in conductivity. The eddy currents would flow unimpeded and there would be no such feature in the data. For the weld at 7.5 J (dotted green line, upper panel) the dip in the data is less pronounced, implying better conductivity, less current deviation, and thus possibly a better weld. In the lower panel of Figure 7, one can compare the 10-J weld (red dashed line) with a weld at the same energy but where the laser was defocused (green dotted line). Defocusing the laser could mean that less energy was available for the weld, and the mechanical strength might not be as good. The trend in the data implies that the defocused weld is at a lower energy than the same weld with the laser focused. The samples still need to be destructively tested to provide final validation, but our initial results are encouraging.

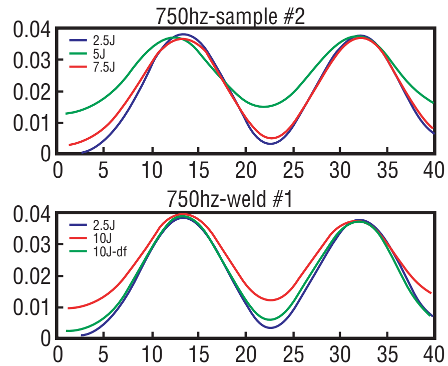

Figure 7. Upper panel: scans of three welds on the same sample. Lower panel: scans of welds in the same position for different samples.

Upset-Forge Welds

The Allied Signal Kansas City Plant invested significant amounts of money developing a reliable new weld technique for reservoirs. They believe this technique will allow them to improve their process—to make their welds stronger and less likely to fail while being less costly. However, they cannot certify a reservoir safe for use without being able to inspect the quality of the weld and quantitatively determine its strength. While destructive tests have shown that the weld technique works, currently no other method tested besides the SAMi (ultra-sound, x-ray, or conventional eddy-current techniques) appears able to tell them the mechanical strength of their welds without destroying them in the process. The other techniques have thus far lacked the sensitivity required to characterize a strong bond from a weak one.

Figure 8. Photograph of two samples, one welded and one solid. The two are visually identical.

Figure 8 shows a photograph comparing a solid and a welded part. The two parts are virtually indistinguishable visually. NDE techniques such as ultra-sound and x-ray also would also have great difficulty distinguishing between the two. Figure 9 shows a SAMi scan of the two parts. The welded and unwelded parts have very different responses.

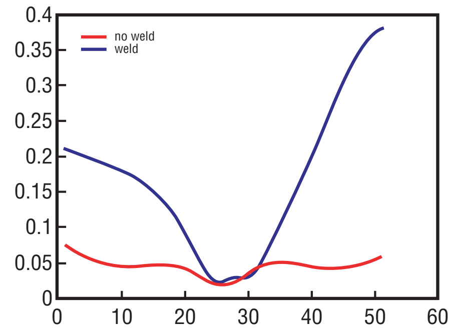

Figure 9. SAMi scans of the solid (red) and welded (blue) upset forge weld samples.

White-Noise Technique

The ability of the white-noise induction scheme to provide depth information was tested with plates of aluminum that were 15 cm × 15 cm and 1.5 mm thick. The distance between the top plate and the dewar bottom was ~2 mm. Holes appear as a two-lobed feature in the data. In Figure 10, the data plots show amplitude vs position for a stack of three plates. The top plate had a 5-mm-diameter hole at x = 40, the middle plate was blank, and the lower plate had a 5 mm diameter hole at x = 10. The bottom hole (4.5 mm deep) is visible at frequencies < 700 Hz where the skin-depth is > 3 mm. As the frequency increases, the skin depth decreases and the sensitivity to the buried feature also decreases. The hole on the top becomes more visible as frequency is increased. The images were acquired simultaneously.

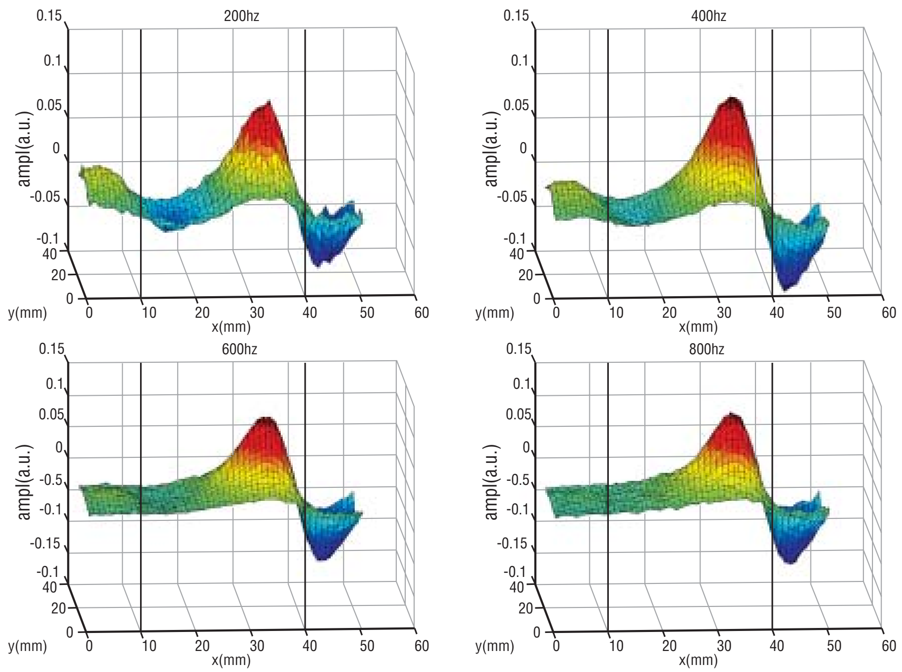

Figure 10. Plots of amplitude vs x-y for 4 different frequencies (indicated at the top of each plot). The sample was a stack of three 1.5-mm-thick aluminum plates. The top plate had a 5-mm-diameter hole at *x* = 40 mm. The middle plate was blank. The lower plate had a 5-mm-diameter hole at *x* = 10 mm.

Summary and Outlook

SAMi is a tool for NDE of unsurpassed sensitivity. SAMi is the first of its kind to use an array of SQUIDs all fabricated on a single chip. The SQUID is the most sensitive detector of magnetic field in the world. SAMi uses eddy current induction methods to induce eddy currents in the sample of interest and then map the magnetic fields produced by the eddy currents. Small features in the sample will cause the eddy currents to deviate and produce anomalies in the magnetic field. These anomalies can be seen even if the feature is very small or buried under intervening layers of conductive or nonconductive material. In cases where the feature of interest is very small, deeply buried, or buried under an insulating layer, the SAMi has strong advantages over conventional NDE techniques. SAMi uses a novel white-noise induction method (patent pending) that induces at multiple frequencies simultaneously, providing information about the depth at which a feature is located.

We have used SAMi to look at a host of NDE problems from small, deeply buried cracks to the inspection of welds. SAMi has proven to be as robust as it is sensitive, and is able to operate without magnetic shielding even in a noisy laboratory environment on room-temperature samples.

It is our hope that other SAMis will be deployed to various laboratory and industrial sites to help solve NDE problems ranging from the stockpile applications to aircraft worthiness.

About the SAMi team

Michelle Espy first came to Los Alamos as a graduate student from the University of Minnesota in 1991. She did her thesis work at the Los Alamos Meson Physics Facility (now LANSCE) and earned her Ph.D. in experimental nuclear physics in 1996. Michelle has worked for the Biophysics Group (P-21) since her graduation, first as a post-doc and more recently as a staff member. She has no plans to live anywhere as flat as Minnesota ever again.

Bob Kraus came to Los Alamos as a postdoctoral fellow with Clark University in 1984 as part of the TOFI collaboration that discovered more than a dozen new light neutron-rich isotopes. In 1986 he joined the Laboratory as the Section Leader of the Ion Optical Design and Magnetic Measurement section of the Accelerator Optics group (AT-3 at the time). In 1994 Bob joined the SQUID sensor effort of the Biophysics group (P-21) where he changed the focus of his work from Tesla accelerator magnets to measuring "femto" Tesla of human brains.

Andrei Matlachov got his Ph.D. in Experimental Physics from the Russian Academy of Sciences, Moscow in 1988. He spent two years as the Deputy Director of Research at the Biophysics Center at the Institute of Radio-Engineering & Electronics in Moscow, Russia and came to America in 1994 to join the staff at Conductus, Inc. Andrei has been a staff member at Los Alamos since 1997.

Pat Ruminer has been at LANL for over fifteen years. He came to the P-21 to work in the SQUID group in 1992. Among Pat's responsibilities has been the design and construction of a large SQUID-based system for measuring the magnetic fields from the human brain.

The SQUID team (including LeRoy Atencio, now retired) won a distinguished performance award for SAMi's single SQUID predecessor in 1997.

Ted Lobb was with the SQUID group from Dec. 1999- Dec. 2000 and has since moved on to ITT Industries in Albuquerque.

John Mosher is currently with NIS-9. John has worked with P-21 for years on the analysis of SQUID-based magnetic field data from human brain function and other projects.

Further Reading

To learn more about SQUIDs:

J. Clarke, "SQUIDs, Brains, and Gravity Waves," *Physics Today* March (1986).

J. Clarke, "SQUIDs." *Scientific American* August (1994).

To learn more about the physics of SQUIDs:

R. P. Feynman, R. B. Leighton, M. L. Sands, *The Feynman Lectures on Physics*, Vol. 3, (Addison-Wesley, Boston, Massachusetts, 1989) 1552 pp.

To learn more about SAMi:

M. Espy *et al*., "A Linear Array of 11 HTS SQUIDS for Non-Destructive Evaluation," *IEEE Transactions on Applied Superconductivity* 11, 1303–1306 (2001).